Experimental Investigations of Nonlinear Internal Wave Generation and Evolution

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LONG-TERM GOALS

The long-term goal of this project is to establish and utilize a state-of-the-art experimental facility for studying the generation and propagation of nonlinear internal tides. This facility will investigate a wide range of scenarios, with the focus being on dynamical regimes at the Luzon ridge. The results from these experiments will interface with analytical and numerical models, improving our ability to model nonlinear internal tides.

OBJECTIVES

The objective of this work is: to identify the dynamical regimes at the Luzon ridge; to determine the nature of the nonlinear internal tides that are generated by the Luzon Ridge in these regimes; and to understand the propagation of these nonlinear tides away from the Luzon ridge. By so doing, we support the development of a predictive capability for the evolution of large-amplitude solitary waves in the South China Sea.

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APPROACH

Our approach is centered around sophisticated laboratory experiments. We fabricate ridges of arbitrary cross section using a CNC foam-cutting machine. The ridge is mounted in a wave tank which is filled with a density stratification. The stratification can be accurately established using a computer-controlled pumping system, which has the ability to set up oceanographically-realistic stratifications with a mixed layer and a thermocline, as well as more simple, linear stratifications. Tidal forcing is simulated by oscillating the topography side-to-side. This motion can be anything from a simple, sinusoidal displacement to a complex motion that mimics the complex tides at Luzon. We can match

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all important dimensionless numbers at Luzon, with the exception of the Reynolds number, so that the experiments are in the same dynamical regime as the ocean; the Reynolds number is still sufficiently high that inertial forces dominate viscosity.

The internal wave field is measured using Particle Image Velocimetry, which provides velocity field data, and Synthetic Schlieren, which provides density-gradient field data. The experimental results are studied to determine the radiated internal tide. Direct comparisons are made with analytical models, which we are also developing, and the predictions of direct numerical simulations. The experimental data provides initial conditions for numerical and analytical models to simulate the evolution of the nonlinear internal tide away from the ridge.

WORK COMPLETED

Since 09/06 we have performed extensive experiments in the new wave tank facility. These experiments have focused on: (i) Investigating fundamental models of internal tide generation, to validate the experimental method; (ii) Running an experiment that is an accurate representation of the Luzon ridge. We have advanced a recent theoretical approach to model the internal tide generated by a Gaussian bump in a finite-depth ocean, incorporating the influence of viscosity so that we can account for this in our experiments. The first set of quantitative results were accepted for publication (Peacock, Echeverri & Balmforth 2007). We have collaborated with the numerical simulations of Jim McWilliams for making comparisons of our Luzon model. Finally, we have identified that the Luzon ridge provides a possibility for the existence of an internal wave attractor, and are further pursuing this issue with R.C. Lien. Both Peacock and his graduate student Echeverri participated in NLIWI cruises in 2007.

The results of these studies were presented at ISSF06, Duke Seminar (Nov 06), Stanford Seminar (Jan 07), APL Seminar (Mar 07) and WHOI seminar (Aug 07). Future presentations are planned for Cornell (Nov 07), APS DFD (Nov 07), Paris (Feb 08) and Ocean Sciences (Mar 08).

RESULTS

(i) Fundamental studies of internal tide generation.

To better understand internal tide generation at Luzon we have studied fundamental aspects of internal tide generation, focusing on the transition from linear to nonlinear regimes. One avenue we are pursuing is the effect of a finite-amplitude excursion parameter, with the goal of determining for what amplitudes the radiated tide can no longer be reasonably modelled using linear models. In this case we have developed a linear model to cope with a Gaussian bump, finite-depth effects and the influence of viscosity in a laboratory-scale experiment. An example set of experimental results is shown in Figure 1. For small-amplitude excursion parameters, the experiments and linear theory are in good qualitative and quantitative agreement. As the excursion parameter is increased, however, the models diverge, with the experimental data showing a distinct asymmetry. An important point is that this discrepancy occurs for tidal excursions that commonly exist at Luzon.

To quantify the state of the internal tide we have developed modal decomposition algorithms for the experimental data, that allow us to extract modal amplitudes from experimental PIV and Synthetic Schlieren data. There are still some technical issues associated with the implementation of these techniques. An example set of data is shown inFigure 2, in which the amplitude and phase of the linear internal tide are compared with theoretical predictions.

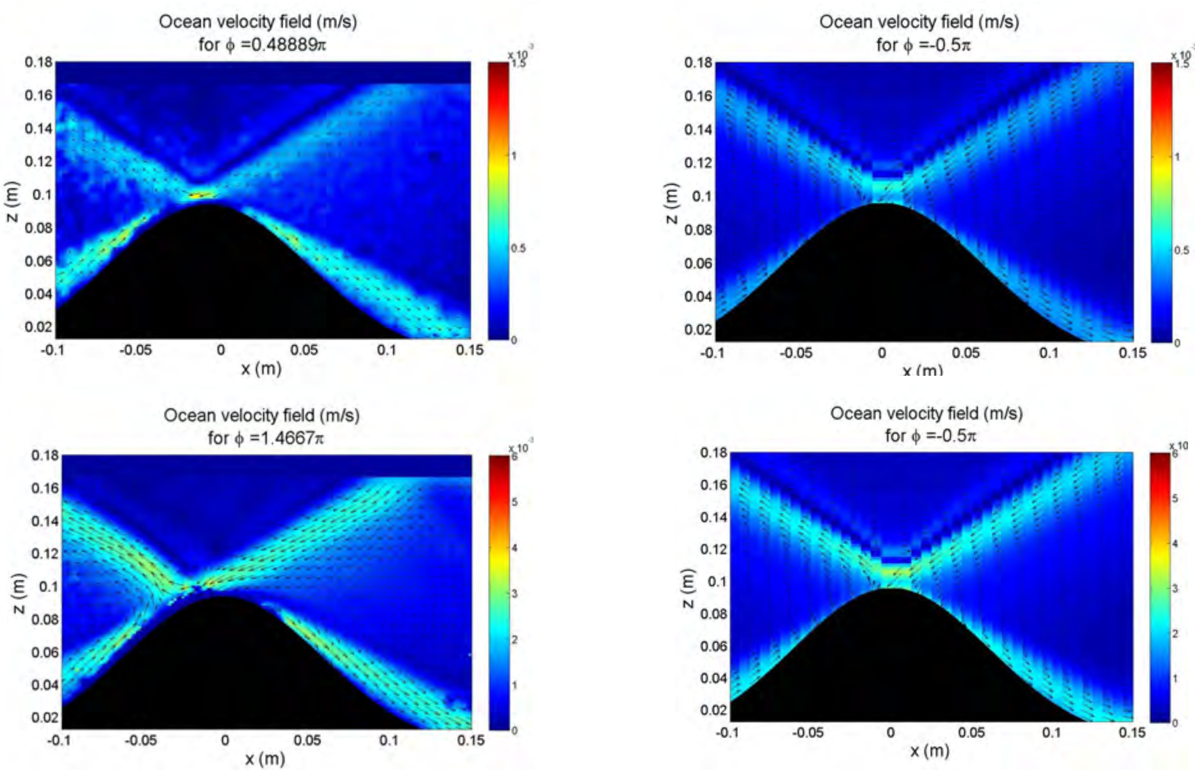

Figure 1: (top row) Experimental and theoretical velocity fields (m/s) for excursion param = 0.01. (bottom row)) Experimental and theoretical velocity fields (m/s) for excursion param = 0.05.

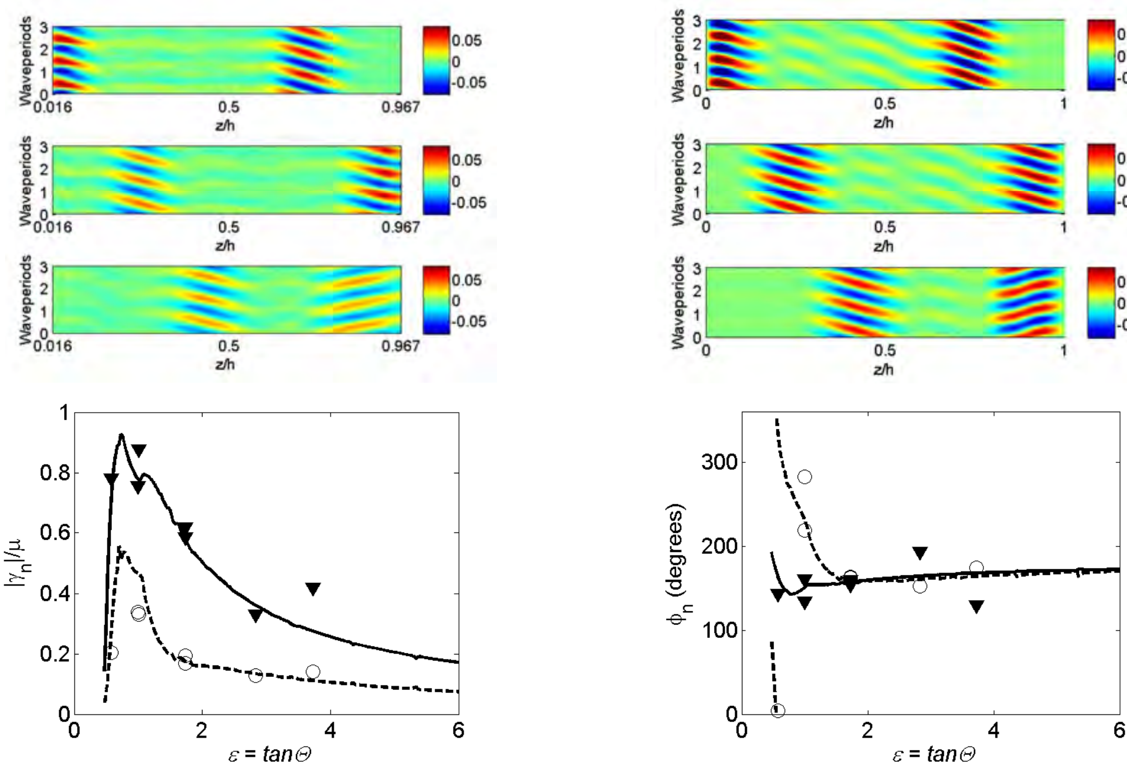

Figure 2: (top row) Density-gradient time-series for three vertical cross sections taken from a Gaussian bump experiment. Experimental (left) and theoretical (right) data. Amplitde (left) and phase (right) of mode-1 (triangle) and mode-2 (circle) plotted as a function of criticality.

(ii) Laboratory modelling of Luzon.

In parallel with our fundamental studies of internal tide generation, we have directly modelled the Luzon ridge in our experimental facility. We set up an experiment with a nonlinear stratification and small-aspect-ratio topography, for which all the important dimensionless quantities matched those at Luzon. A summary of the physical and dimensionless parameters for Luzon and the experiment are shown in Table 1. Velocity field date from the experiments is shown in Figure 3. We are in the process of analyzing these results for comparison with numerical simulations and field data.

Depth H	3.5×10^3 m
Topographic height h	3×10^3 m
Topographic width L	5×10^4 m
Topographic slope (typical)	0.12
Stratification N max (thermocline)	10^{-2} rad/s
Stratification N min (bottom)	10^{-3} rad/s
Tidal frequency ω	1.41×10^{-4} rad/s
Maximum tidal current u max	0.6 m/s
Far field tidal current $u0$	0.084 m/s
Beam slope s (thermocline)	0.026
Beam slope s (bottom)	0.13

Depth ratio h/H	0.86
Aspect ratio h/L	0.06
Excursion parameter $u0/\omega L$	0.012
Criticality $(dh/dx)/s$	$0.9 - 2$
Horizontal Froude at topography peak $u\max/N\max L$	0.0012
Vertical Froude at topography peak $u\max/N\max h$	0.02
Reynolds number $u0h/\nu$	1.8×10^9

Depth H	0.127 m
Topographic height h	0.10 m
Gaussian width $L = 4\sigma$	1.0 m
Tidal frequency ω	0.09 rad/s
Oscillation Amplitude A	6 mm, 12 mm
Buoyancy frequency N	1.2 rad/s (max)
Thermocline location	-0.0175 m

Depth Ratio (h/H)	0.79
Aspect Ratio $(h/4\sigma)$	0.1
Excursion Parameter $(A/2\sigma)$	0.012, 0.024
Criticality at $x = \sigma$	1.33
Horizontal Froude at topography peak $\omega A/NL(1 - h/H)$	0.00225, 0.0045
Vertical Froude at topography peak $\omega A/Nh$	0.025, 0.045
Reynolds number $(\omega A/(1 - h/H))\sigma/\nu$	675, 1350

Table 1: (left) Physical and dimensionless parameters at Luzon. (right) Physical and dimensionless parameters in the experiment.

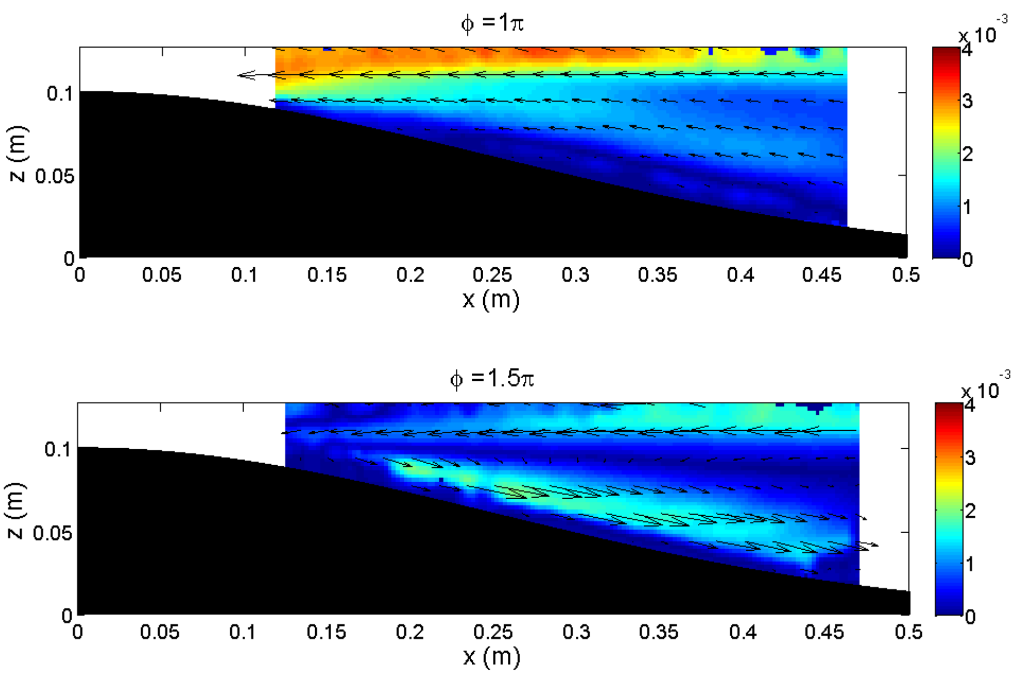

Figure 3: Velocity field data from experimental simulation of Luzon. (top) peak westward tidal current. (bottom) zero tidal current.

(iii) Internal wave attractors.

We have identified that the double-ridge geometry at Luzon provides a configuration that can support the existence of an internal wave attractor, which is a closed ray path that attracts all neighbouring ray paths (Manders, Maas & Gerkema 2004). An image of the attractor is shown in Figure 4. A consequence of the existence of this attractor is expected to be regions of intense instability and mixing due to a focusing of internal wave energy. In collaboraiton with R.C. Lien, we are investigating the robustness of this structure, and the feasibility of actually observing it in field data and numerical simulations.

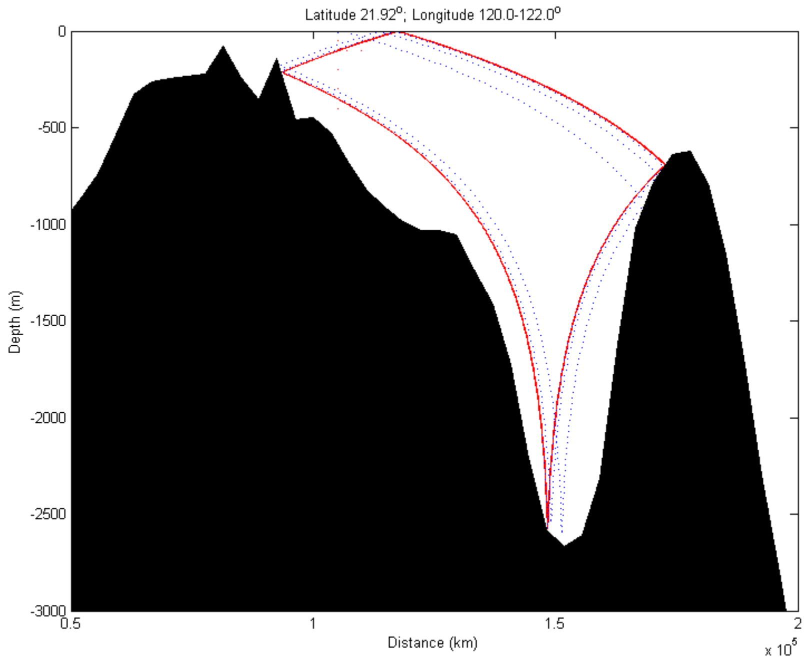

Figure 4: An internal wave attractor at the Luzon ridge.

IMPACT/APPLICATIONS

We have obtained the first laboratory experimental results concerning the generation of internal tides by ocean ridges. There has been much demand from numerical modellers and field researchers for the data generated by these experiments, to validate numerical models in highly nonlinear regimes. Furthermore, these experiments have tested the practical limits of analytical models, which we continue to develop. Another application of the experimental data is to interpret ocean data from the recent Luzon field studies, in collaboration with David Farmer.

RELATED PROJECTS

There are four projects with which we have developed, or are in the process of developing, close collaborations. For the fundamental studies of internal wave generation by a Gaussian bump, we are collaborating with Kraig Winters at Scripps. We will directly compare our experimental results with the prediction of his numerical simulations, with the goal of identifying processes by which models of linear internal-tide generation break down. For the laboratroy modelling of Luzon, we continue to collaborate with Jim McWilliams at UCLA. Our experimental results obtained in summer 07, examples of which are presented in Figure 3, have now been simulated using the ROMS model. We are in the process of making a comparison of the two sets of results. Once we have achieved good agreement in the near field, the numerical model can be confidently used to simulate the far field evolution of the tide. After the recent Alaska meeting, we have begun a collaboration with David

Farmer to study how the sill (or sills) at Luzon can lead to the observed internal tide at his A1 station; and we are collaborating with R.C.Lien on the study of internal wave attractors at the Luzon ridge. Finally, both Peacock and his graduate student Echeverri participated in NLIWI cruises with Steve Ramp and Craig Lee, respectively.

REFERENCES

A.M. Manders, L.R.M. Mass & T. Gerkema, Observation of internal tides in the Mozambique channel, *JGR* 109, C12034 (2004).

PUBLICATIONS

T. Peacock, P. Echeverri & N.J. Balmforth, An experimental study of internal-tide generation by two-dimensional ridges, to appear in *JPO* (2007).

HONORS/AWARDS/PRIZES

1. Thomas Peacock (MIT), NSF CAREER Award, “From the lab to the ocean”.